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PRELIMINARY REVIEW OF FLOW MODELS CONSIDERED
FOR USE AT VANDENBERG AIR FORCE BASE

by

R. F. Kamada

February 1989

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FOR USE AT VANDENBERG AIR FORCE BASE

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ABSTRACT

NPS reviews several diagnostic and prognostic mesoscale windflow models which are currently being considered for use in evaluating plume releases at Vandenberg Air Force Base. Some issues considered are the various model implementations of: 1) objective analysis, 2) mesoscale meteorological physics, 3) domain size, grid spacing and nesting, 4) lateral, top, and bottom boundary conditions, 5) solution methods, 6) validity of surface layer similarity in complex terrain, 7) temporal variations in the wind field, 8) and model running time and computer power. We also describe possibilities for certain advances in diagnostic windflow modeling and draw conclusions concerning current and future modeling applications for Vandenberg.

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GLOSSARY

advection	transport by mean (usually horizontal) wind
boundary layer	first 100 - 3,000m of atmosphere, characterized by turbulent mixing
buoyancy force	force based on gravitational settling of dense layers of fluid under less dense layers
chimney effect	Heated air expands, losing density with respect to its surroundings and rises, as in a chimney, a regular daytime event along mountain ridges.
complex terrain	inhomogeneous terrain (as at Vandenberg with shorelines, valleys and mountains)
convergence	general confluence of an air mass shown by converging flow streamlines. Leads to upward motion in the convergence zone. (see divergence and mass consistency).
diagnostic	Diagnostic computer models neglect time changes and thus are descriptive rather than prognostic
diffusion	dispersion due to turbulence rather than transport by the mean wind flow
dispersion	combined transport/diffusion of plumes due to mean wind flow and turbulence
divergence	spreading of an air mass indicated by diverging streamlines. Leads to downward (subsiding) air in the divergence zone.
downslope drainage	A cold sloped surface cools nearby air. This denser cooled air moves downslope, creating a drainage flow.
drag	friction or surface shearing stress
eddy	semi-coherent turbulence structure with quasi-periodic rotation about a central vortex tube
empirical	based upon data taken in real conditions
finite difference models	solve the governing equations at each point on a grid arbitrarily imposed on the domain of interest
front	a narrow transition zone between two air masses having different temperatures, densities, and winds.

hydrostatic assumption	that the pressure at any point is unaffected by lateral or vertical air motions and is given by the weight of a column of air above it having a unit cross section. This implies that vertical velocities are not subject to acceleration, laterally advective, or turbulent forces.
inversion	air layer having a large positive vertical potential temperature gradient
leeside	downwind side of a mountain ridge
mass consistency	Mass conservation and incompressibility limit atmospheric motions. Convergence at one height means divergence at another height and vertical motion between them. Mass consistent models follow these constraints.
meander	plume response to turbulence larger than a plume's transverse width
mesoscale	scales from ~ 1 to 1,000km
meteorological tower	mast mounted with sensors at various heights to measure temperature, wind speed and direction, humidity, pressure, etc.
mixed layer	well mixed boundary layer with nearly constant potential temperature and water vapor mixing ratio (usually seen in convective conditions)
nested grid	a finer mesh grid surrounded by one or more grids having a coarser mesh
neutral	see stability and buoyancy force
objective initialization	initial input from tower, sodar, balloon, sonde and other data.
objective correction	correcting model results according to real data
periodic boundaries	see p. 16.
plume	airborne discharge from a continuous source

potential temperature	temperature of an air parcel or layer adjusted for heating or cooling due to pressure changes with height (assuming no heat exchange with the environment)
prognostic	Prognostic models have time derivatives of the variables of interest and thus are predictive.
puff	airborne discharge from an instantaneous single release (a burst)
radiative boundary conditions	designed to allow wave motions to radiate out beyond the boundaries rather than be reflected artificially by model boundaries (see p. 13).
sodar	(sound detection and ranging). Acoustic backscatter from density gradients gives inversion height and strength. Doppler sodar (DASS) also gives winds.
sonde	balloon equipped with a radiotransmitter giving temperatures, pressures, humidities or winds as it ascends
spectral models	approximates the flow with a series of sine and cosine waves or other functions and solves the governing equations for each wave number. (see p. 16).
stability	Dense air below (positive potential temperature gradient) is stable because initially random upward motions are damped by buoyancy forces. Dense fluid above is unstable, since buoyancy will boost upward motions. Neutral air lacks a density gradient and is unaffected by buoyancy.
stagnation	mean horizontal wind speeds less than 1 knot.
stratus cloud	a type of layer cloud caused by general lifting of an air mass. The bottoms or tops of such clouds often coincide with the top of a well-mixed boundary layer.
streamlines	snapshot of the velocity field at a single instant as opposed to trajectories over time
subsidence	general sinking motion of an air mass
surface drag	frictional drag induced by terrain roughness and also the fact that the wind speed must drop to zero at the surface (no slip condition).

synoptic scale	scales from 1,000 to 10,000km at which weather determining phenomena appear
turbulence	chaotic fluid motions over periods shorter than the averaging time over which the mean motion is defined. Thus, the portion of flow regarded as turbulence varies in practice with ad hoc issues such as the model's time resolution.
turbulent transport	the diffusion of momentum by the turbulent part of the flow. This diffusion occurs in a highly non-linear fashion which is often modeled by linear or second order approximations.
turbulent kinetic energy	the kinetic energy contained in the turbulent portion of the total flow
unstable	see stability and buoyancy force
upslope flow	Heating of sloped terrain warms and lightens air near the surface more than air at the same height but laterally further away. Buoyancy acts on the induced density difference to move air near the surface further along the slope, producing an upslope flow.

BACKGROUND:

In February, 1988 NPS reviewed ENSCO's report on options for an operational wind flow model at Vandenberg AFB. After reviewing the SRI COMPLEX (Endlich and Ludwig, SRI), LINCOM (Ib Troen, RISO), AFWIND (Ball, Johnson, and Lanicchi, AFGL), and HOTMAC (Yamada, LAL) models, ENSCO recommended SRI COMPLEX (also known as Winds on Critical Streamline Surfaces or WOCSS) as the best available for Vandenberg's immediate needs.

Since Vandenberg has accepted this recommendation, NPS is comparing SRI COMPLEX with LINCOM, a flow model from RISO Labs (Denmark). Steve Hunter, ex-Flow/Diffusion modeling officer at Vandenberg has begun testing SRI COMPLEX at RISO with help from Drs. Ray Kamada and Torben Mikkelsen. Flow fields from LINCOM and SRI COMPLEX will drive RISO'S puff model, RIMPUFF. Outputs are being compared with eight typical cases from the Vandenberg Mt. Iron tracer studies of 1963-64. Though issues remain, we are now familiar enough with these and other models to present our own preliminary review. On the basis of items noted during and after studying their report, we reach conclusions rather different from those of ENSCO. Part of this review will appear in Appendix F of the Vandenberg Meteorology and Plume Diffusion Handbook and a final report on the Mt. Iron comparison.

Prior to in-depth discussion, we display a tabular summary which includes the newly available RAMS model from Drs. Roger Pielke and William Cotton of Colorado State University. White Sands Missile Range's version of SRI COMPLEX is not included because we have not yet received their model documentation.

Table I: SUMMARY OF MODELS CONSIDERED FOR VANDENBERG

	LINCOM	SRI COMPLEX	AFWIND	HOTMAC	RAMS
< 5 CPU min. on Microvax II	+	+	-	-	-
Model type	diagnostic linearized	diagnostic Froude #	diagnostic min accel.	prognostic primitive	prognostic primitive
objective initialization	+	+	+	+	+
objective correction	+	-	-	+	+
unstable physics: seabreeze, upslope flow	-	-	-/+	+	+
neutral physics: pressure, shear drag	+/-	-	-	+	+
stable physics: drainage, land breeze	-	-/+	-/+	+	+
mass consistency	-/+	-/+	-	+/-	++
treats steep slopes	-/+	-	-	-/+	+
non-hydrostatic effects	-/+	-	-	-	+
treats clouds	-	-	-	+/-	+
Turbulent transport	1st order	-	-	2nd order	2nd order
Turbulent kinetic energy	-	-	-	***	+/-
radiation, cloud physics	-	-	-	+	+
nested or telescoping grid	+	-	-	+	+
Vertical layers	2 nested	6	1	10 - 20	10 - 30
Top boundary of domain	flat w = 0	K.E./P.E. balance	terrain following	constant value	g wave radiation
Lateral boundaries of domain	periodic with terrain relaxation	?	?	closed, & 0 gradient	radiative
Solution method	spectral/analytic w/ look-up table	***	*** iterative	*** ADI	***time split

+/- and -/+ indicate greater or lesser degrees of partial fulfillment.
 * includes subgrid density fluctuations, i.e., full mesoscale primitive
 ** includes prognostic equation for turbulence dissipation length scale
 *** finite differencing scheme
 ADI refers to alternate direction implicit method (see p. 17)

INTRODUCTION

The near mutually exclusive model physics and speeds shown in Table I suggests that a model selection scheme is needed for optimal results. However, further scrutiny indicates that basic inadequacies exist in some models and others need improvement.

The following discussion includes some issues which affect model accuracy, speed, and applicability that are not mentioned in the ENSCO evaluation. Major issues are 1) the blend of objective analysis with the physics included in the predictive equations, 2) grid spacing, nesting, and vertical levels, 3) domain size and boundary conditions, 4) validity and efficacy of numerical methods used, 5) validity of similarity scaling in complex terrain, 6) temporal differences between models with regard to wind meander and flow separation, 7) computer power. We close with comments on possible projected improvements to LINCOM and give summary conclusions concerning the models in general.

OBJECTIVE ANALYSIS

Since Vandenberg is so densely monitored with 27 towers, 3 sodars, radio and rawindsondes, and soon a doppler radar wind profiler, models making optimal use of objective analysis are obviously preferred. Any review should mention that all models combine objective analysis with some incomplete subset of the real physical equations. When used for correction, objective analysis restores much of the missing physics. LINCOM, HOTMAC, and RAMS use tower data for both initialization and correction. Hence, these models function as fancy interpolators incapable

of straying too far from data values. In fact LINCOM's output matches the tower winds exactly, rather than tends toward them as in HOTMAC. However, the SRI COMPLEX and AFWIND models use objective analysis only for initial input. If conditions exceed the scope of the model physics, these models will stray from their initial measured values without further correction. The ENSCO report omits this issue.

The Vandenberg Meteorology and Plume Dispersion Handbook assessed 100 cases involving 10 typical Vandenberg flow types, using LINCOM. The objective analysis used a weighted inverse distance squared interpolation of 11 towers at 500m resolution over a 25 x 40 km domain. SRI COMPLEX runs on a 2 km grid on a smaller domain at Diablo Canyon, using 6 towers and 4 sodars.

MODEL PHYSICS

THE PHYSICS IN LINCOM

With regard to assumed physics we repeat that LINCOM, SRI COMPLEX, and AFWIND are basically mutually exclusive. That is, LINCOM is presently well designed for non-buoyant (neutrally stable) atmospheres. It computes the way the mean flow deviates due to advection, turbulence, and terrain induced surface drag and pressure gradients. It neglects acceleration (time changes in flow velocity). Thus, like SRI COMPLEX and AFWIND, it is a diagnostic, rather than prognostic model. Its primary merit is its ability to estimate the very real speed up effect of slopes on winds within the surface layer (first few tens of meters). In keeping a linear basis, LINCOM simulates turbulent transport only to first order. It also neglects the heating or cooling of

surfaces. Hence, it does not treat seabreezes or slope flows on scales smaller than that included in the mean flow over the domain. LINCOM is not hydrostatic. It treats non-hydrostatic vertical motions due to advection and diffusion, but neglects buoyancy effects and accelerations.

However, our recent unpublished analytic study shows that heating/cooling effects rise with the square of the horizontal scale. Thus, the seabreeze (included in the mean flow) remains important, but local heating/cooling is secondary to mechanical pressure/drag. Indeed, objective corrections restore some small scale thermal effects. It is also possible to add such effects directly to LINCOM, using an imposed temperature field.

LINCOM also uses linearized momentum equations which do not fully capture site variations in the advective terms. Both LINCOM and SRI COMPLEX obtain surface vertical wind speeds from the slope angle and horizontal wind speed, assuming that slopes are modest. Julian Hunt, who originated LINCOM's model class, says the method is accurate for slope aspect ratios up to $1/4$ and useful for ratios up to $1/2$. Even if we question the latter figure, objective correction mitigates most of LINCOM's errors.

Though LINCOM includes a mass conservation equation, true mass consistency is partly compromised when the perturbed winds surrounding each separate mean tower wind are all combined into a final output wind field. LINCOM also assumes flat inversions. For several reasons, inversion heights actually vary substantially over the Vandenberg region. This further compromises mass consistency, since the total domain volume and its upper level

features are not well assessed. Note that Vandenberg sondes are launched only at 0400 and 1600 LCT, have poor boundary layer resolution, and the three doppler acoustic sounders are located away from the rugged, inland terrain. Also, the diagnostic models all restrict their domain to the boundary layer. Hence, there is the problem of determining when towers (data points) lie above the inversion and thus should be ignored. Our new complex terrain inversion height algorithm may help resolve this modeling input problem in the future.

THE PHYSICS IN SRI COMPLEX

During stable conditions, SRI COMPLEX estimates the height which an air layer reaches moving up along a hill, and thus the decrease in its thickness, by balancing the layer's kinetic energy at the bottom of the hill against the negative buoyancy the layer accrues as it rises. Once the layer height and thickness is set, wind speed and direction are determined by mass conservation within the layer. In determining the kinetic/potential energy balance, surface drag and shear between layers are ignored.

The method does not apply to unstable seabreeze or upslope flows, or stable land breezes. That is, SRI COMPLEX's major limitation (unmentioned by ENSCO) is that the positive buoyancy accrued by a layer in unstable conditions is empirically treated rather than included in the physics. Meanwhile, the mechanical forces which are present under all conditions are entirely neglected. Moreover, since the output is uncorrected, flows can stray from measured data, even in stable cases.

Indeed, the energy balance used actually requires wind speeds in low lying terrain to be supplied by or extrapolated from tower data. The procedure presents some problem at Vandenberg since low lying towers such as 009 often show considerable channeling away from the general flow direction. Thus, initial vectors must be largely extrapolated, rather than interpolated. The extrapolation procedure requires that deviations from the neutrally stable, log-normal wind speed vs. height profile be measured for each of the towers. The extrapolation procedure then assumes for low lying areas that the deviations recorded at the nearest tower will be maintained. As in the common cases of a nearby tower sited in an area with significantly different surface roughness, atop a ridge, or on the other side of a stratus cloud front, this assumption is not always justified.

Since the SRI model consists of several layers in the vertical with separate mass budgets within each layer, mixing between layers is not allowed. This precludes the modeling of intra-boundary layer circulations. In fact, mass consistency is not always maintained in each layer. That is, mass continuity is indicated by sets of streamlines. Where a streamline fails to sweep over some terrain which blocks the flow, the associated mass is transferred to neighboring streamlines. However, in box canyon situations, when too many streamlines end in these so-called stagnation points, mass consistency is thwarted.

THE PHYSICS IN AFWIND

AFWIND truncates the fluid momentum equations to a balance between acceleration, advection, and buoyancy. Then, by minimizing the overall acceleration over the domain, it operates by shifting the initial wind vectors until they balance the local buoyancy forces. Thus, AFWIND is a pure up/down slope flow model which neglects drag, shear, mechanical pressure, mass conservation, and the larger scale horizontal temperature gradients which drive the seabreeze.

Moreover, the solution method is based on pushing the model away from the measured winds. In fact, the obtained solution is not necessarily unique, but may be only one of many which satisfy the model balance. Hence, the final wind field need not even resemble the measured flow. Also, due to some internal problem, convergence to the true minimum is not assured. In practice, Lanicchi and Weber (1986) settle for a local minimum which has no clear physical meaning.

In order to assess small scale slope flows which routinely improve on objective analysis (as implied in Lanicci and Weber) AFWIND also needs precise vertical temperature profiles from the towers. This requires frequent tower thermistor contact calibrations and some regression formula which judges the internal and external consistency of the readings from each tower. However, the AFWIND model now accepts data from only two heights per tower. This precludes any regression. The thermistor issue also applies to the appraisal of buoyancy forces in both SRI COMPLEX and any improved version of LINCOM.

THE PHYSICS IN HOTMAC

HOTMAC contains most of the physics significant to the mesoscale. Its fully non-linear momentum equations include the buoyancy term now missing in LINCOM. It also has temperature, water balance, and static mass continuity equations. HOTMAC simulates turbulent advection to second order by using the turbulence kinetic energy equation. However, the vertical profiles of pressure are wholly due to thermally induced density differences, i.e., it assumes the atmosphere is hydrostatic and ignores advection, acceleration, and drag in the vertical momentum equation. This is all right for shallow slopes, greater stabilities, and grid spacings larger than a few kilometers. However, a 0.5 - 1.0 km spacing is needed to show that plumes at Vandenberg can entrain into the boundary layer via local subsidence over valleys and canyons, while slope heating may cause chimney type outflows along the ridges. Because HOTMAC is hydrostatic, it also cannot properly account for cumulus clouds where vertical motions are important.

The water balance, microphysics, and radiation budgets do let HOTMAC treat the stratocumulus which diagnostic models all avoid. However, HOTMAC has trouble predicting the position and critical timing of stratus deck burn-off. That is, day-time stratus burn-off is determined by competition between the cloud front's onshore advection and the surface warming due to solar heating. As the heating increases, the burn-off feeds itself by letting sunlight reach the surface. This then augments the seabreeze and slope flow forces. But reduced heating under the

cloud suppresses turbulence and thus plume diffusion. This amplified "all or nothing" feedback lets small initial errors produce large errors in predicted local flow and diffusion.

One source of initial error is soil/vegetation canopy moisture. Surface temperature and hence sensible and latent heat fluxes depend on a surface energy balance involving soil/canopy heat transport. The transport varies with moisture content and cannot be determined accurately without data.

Perhaps another reason for HOTMAC's stratocumulus problems is that it does not compute phase velocities accurately for the shorter internal gravity waves. This may allow energy and thus condensation/evaporation to appear in the wrong locations.

THE PHYSICS IN RAMS

Unlike HOTMAC, RAMS includes non-hydrostatic terms in its prognostic primitive equations. This allows more accuracy for clouds, convective cells and steep, small scale slope flows in complex terrain. RAMS treats both strato and full cumulus behavior, but not rain. It also treats the sub-grid scale density fluctuations neglected in HOTMAC's mass budget. However, NPS plans to add a diagnostic dissipation length scale to RAMS' turbulence kinetic energy budget to improve RAMS ability to accurately simulate convective boundary layers.

DOMAIN SIZE, GRID SPACING AND NESTING

A primary criterion for operations is that a model be able to treat a 50 x 80 km domain at ~ 0.5 - 1.0 km grid resolution. In fact the 1.0 km limit used in ENSCO's report may not suffice

for complex terrain near a release site. Yet, modeling the seabreeze/slope flow requires an inland domain size of ~ 100 km. The current, stringent toxic exposure limits also suggest long downwind ranges for plumes. Without stretched or nested grids, it is currently difficult for models to account for both the required small grid spacing and a large domain size.

For example, SRI COMPLEX needs 2 Mbytes storage for a 25 x 40 km grid, still too small to treat long range transport. However, a form of LINCOM, called BZ, uses a stretched grid drawn in radial coordinates. HOTMAC and RAMS use two-way interactive grid nesting. However, HOTMAC's 2/1 mesh ratio at best leads to a 2 km mesh outer grid. RAMS, on the other hand, allows multiple meshes with ratios up to 5/1. RAMS developer, Dr. William Cotton, also claims that RAMS' nested interfaces do not induce serious artificial wave reflections. This claim is being investigated. Stretched grids also induce artificial wave reflection. However, for diagnostic models this is hardly a problem, since such pseudo waves cannot gather energy over time because the model lacks temporal dimension.

Other effects of changing grid spacing should be addressed. For example, at an operational 1km resolution, AFWIND, which is designed for small scale slope flows, will miss some canyons (such as Honda) whose floor to ridge distance is less than 1km.

Moreover, there is a terrain aliasing problem. That is, highly local winds around the towers can distort the predicted winds. For example, none of the models can predict the degree of ridge top speed-up and veering at towers 055 and 056, even

with a 0.5 kilometer mesh because the effect is very local. However, through objective analysis, mass continuity, pressure perturbations, etc., a local effect can distort the results in other parts of the domain. LINCOM mitigates this by giving low weight to such stations in the objective analysis.

VERTICAL LEVELS

Other factors being equal, increasing the number of layers in the vertical should enhance the accuracy of a finite difference model. AFWIND is a one layer model which ignores influences above the surface layer. SRI COMPLEX employs 4 - 6 layers, initialized by sodar/sonde extrapolations. Again, HOTMAC and RAMS are more complex, using ~ 10 - 30 layers, closely spaced near the surface to match the scale of the turbulent transport, and stretching further out as the dominant wave lengths grow.

However, LINCOM uses matrix inversion rather than finite differencing. For each wave number, the solution is expressed as the sum of two terms. The first is associated with the sharp gradients in the first few tens of meters (surface layer) because it varies rapidly with height, while the second correlates with slower changes occurring in the outer boundary layer. Similarity theory is used to set the constants. With this approach LINCOM should be more accurate than an analogous two or even several layer finite difference model.

LATERAL, TOP, AND BOTTOM BOUNDARY CONDITIONS

For a mass consistent model requiring continuity at the

lateral and top boundaries, the general idea is to minimize artifacts. Common approaches are to extend both lateral and top boundaries well beyond the region of interest, sponge them, and filter out artificial waves created by boundary reflection. Thus, LINCOM adds artificial buffering terrain which slopes gradually back to sea level before reaching lateral boundaries. However, SRI COMPLEX has no buffer zone. Without mass transfer between layers, intra-layer continuity can only be maintained by balancing the flow into the domain with flow out. However, discussions with the authors have not yet clarified this issue. On the other hand, the AFWIND model claims no mass consistency. Thus, no special boundary conditions are required. Ideally, HOTMAC's lateral boundaries are placed some distance from the region of interest. The boundary on the inflow side is assumed to be unaffected by downstream flow perturbations (closed boundary), while horizontal gradients of each variable are assumed to vanish at the outflow boundary. This method prevents wave reflection at the outflow edge but does not properly handle upstreaming internal gravity waves reaching the inflow side. Again, RAMS is more sophisticated, since it has an option for radiative boundaries which diagnose the dominant phase speed of internal gravity waves and alter the variable values at the lateral edge to minimize reflection.

LINCOM uses a flat inversion with zero velocity at the top boundary. This induces some artificial pressure redistribution. SRI COMPLEX computes its inversions using critical streamline height. This again gives unrealistic flat inversions in neutral

and unstable cases, but more realistic semi-terrain following inversions in stable cases. The one layer included in AFWIND of course parallels the terrain. In HOTMAC and RAMS the domain top lies well above the boundary layer and thus presumably away from most of its influence. In HOTMAC temperature, winds, and humidity are unchanging at the top boundary and the turbulence kinetic energy vanishes. RAMS again applies a refined gravity wave radiation condition to its top boundary.

We have already commented on some aspects of the bottom boundary conditions. The main distinction is that diagnostic models assume surface and surface layer conditions based, at least initially, upon tower data which force the flow without feedback. Prognostic models may be similarly initialized. Subsequently, however, they use a surface energy balance to compute surface temperatures and hence fluxes. This technique allows the feedback between flow and surface temperature fields required to predict temporal changes. However, the energy balance includes soil/vegetation heating/cooling which depends largely upon soil moisture and vegetative evapotranspiration, terms difficult to estimate.

The other significant item is again that LINCOM and SRI COMPLEX both assume a surface vertical wind simply based on the sine of the slope and the nominal horizontal wind speed. This approximation only holds well for modest slope angles.

THE INVERSION PROBLEM

Though RAMS should do best, none of the models account well for inversions which intersect the terrain. In LINCOM

flow passes both over and around the truncated peak by pressure and continuity. In SRI COMPLEX some streamlines will simply terminate as in the stagnation point problem mentioned earlier. AFWIND ignores these problems by addressing only the surface layer flow.

The inversion problem in HOTMAC and RAMS is quite subtle, and common to all prognostic, primitive equation models, but rarely discussed. That is, hydrostatic balance implies that the potential temperature varies logarithmically with height, but such models use a mean potential temperature between vertical nodes which is computed by some weighted finite difference technique. Since small weight differences between atmospheric columns exert a profound effect on horizontal accelerations, the small differences between the estimated and actual form of the potential temperature variation will introduce artificial accelerations which can radically augment the true windspeed over the period of time simulated.

To suppress this artifact horizontal diffusion is usually artificially boosted. However, this then adds unreality to the simulation. Accurately assessing the weight of an atmospheric column is even harder when a kink in the potential temperature profile, which indicates the presence of an inversion, moves between grid levels. Or worse yet, when such an inversion kink disappears into or emerges out of intersecting terrain.

SOLUTION METHODS

Numerical methods used in the models affect the stability, speed, and accuracy of the results. The pseudo-spectral method

which transforms the lateral equations into Fourier wave number space is inherently more stable than finite difference schemes, but more trouble when specifying boundary conditions. That is, the spectral method assumes that the domain's terrain is continuous and repeated periodically ad infinitum. In large scale general circulation models, terrain discontinuity at the east-west boundaries is avoided, since the earth is a sphere.

However, LINCOM avoids discontinuous terrain at mesoscale lateral boundaries by adding artificial terrain which gradually slopes back to sea level. This induces upstream and downstream errors, somewhat mitigated by domain enlargement. LINCOM also avoids the temperature equation because it allows propagating gravity wave solutions which distort the lateral streamlines. Due to the spectral model's assumed periodic domain, such waves will leave the domain only to re-enter again artificially from the upstream edge, falsely propagating throughout the domain.

However, for LINCOM, the spectral method's chief advantage is that linear equation sets have analytic solutions for each wave number which apply over the whole domain. The wave solutions are summed to obtain the total flow. Such sums may also be pre-calculated so that flow fields are obtained by interpolation from look-up tables. The nearly frictionless flow in the outer layer allows this procedure and makes LINCOM operationally extremely fast.

The other four models use much slower finite difference numerical solutions. We have already discussed problems with AFWIND's iterative technique. With regard to cloud formation/

dissipation we have also seen that HOTMAC's alternate direction implicit finite difference scheme may not accurately compute phase velocities for fast internal gravity waves. Thus, energy (used for cloud processes) may appear in the wrong locations. To treat such fast internal waves, RAMS solves the hydrostatic and elastic parts of the flow equations separately. Because compression creates high speed sound waves, a much smaller time step is used for this part than the anelastic part of the flow.

VALIDITY OF SURFACE LAYER SIMILARITY IN COMPLEX TERRAIN

The surface layer wind and temperature profiles assumed by the LINCOM, SRI COMPLEX, and AFWIND models are based on Monin-Obukhov similarity theory, valid for horizontally homogeneous terrain. This constraint is obviously violated at Vandenberg. Indeed, changes in surface roughness will introduce kinks in the profiles. Downstream, these kinks will occur at heights roughly one tenth the distance from the roughness change. This is especially serious for the SRI COMPLEX and AFWIND models because, as discussed above, the input to their uncorrected physical equations relies on extrapolations from assumed profiles. We at NPS are attempting to obtain enough data in our on-going Vandenberg field studies to test the suitability of certain modifications to the standard similarity profiles.

Another terrain effect is that the surface layer height varies, not only with surface roughness, but also slope. That is, the surface layer height over a ridge is roughly 1/10th the horizontal distance from the bottom to its half-height, but only LINCOM, HOTMAC, and RAMS treat this feature explicitly.

TEMPORAL VARIATIONS IN THE WIND FIELD

LINCOM, SRI COMPLEX, and AFWIND produce only single snapshots of the flow. Only RAMS and HOTMAC predict any temporal change. Thus, diagnostic models yield final wind fields in much less computer time. However, when coupled with a puff/plume diffusion model, the results become less relevant as transport time increases because the assumed steady state wind field gradually loses validity. One can update the wind field used to drive the puff model by feeding new tower inputs into a diagnostic flow model, say every few minutes. However, the flow model must then run fast enough on the host computer for this method to be useful. With diagnostic models an ad hoc, random Monte Carlo element must also be inserted in puff models to account for the lack of temporal changes in the wind field.

The problem also occurs for pre-launch forecasts, but again in practice we can partly mitigate this by using interpolations between current data and the next synoptic scale forecast to supply estimated changes in the mean flow field. However, in this case, the predicted fields will remain uncorrected by objective analysis, since tower data will not have been taken yet. Under these conditions models such as HOTMAC and RAMS will have a definite advantage, mitigated only by the issue of whether they can be run faster than real time (see below).

During high winds, terrain obstacles can separate the flow and shed highly turbulent vortices. AFWIND and SRI COMPLEX do not deal with this condition and it is unlikely that any hydrostatic models can properly treat this situation either.

MODEL RUNNING TIME AND COMPUTER POWER

Vandenberg requires that THC forecasts be available within 10 minutes. This includes punching values into the input menu, outputting a gridded wind field, and displaying plume trajectories and concentration isopleths within a defined THC. Since ENSCO runs MARSS with a simple puff model on a MicroVAX, they should be able to estimate a maximum time allottable to the flow model, including input/output. Their report allows 5 CPU minutes. However, this will vary with windspeed, turbulence, etc. Thus, the 10 minute limit should apply to a fairly slow, but not worst plausible test case. If so, we have assumed in Table I that the allowed CPU time for the flow model alone will be well under 5 minutes.

Only LINCOM and perhaps possibly SRI COMPLEX can meet this constraint on a MicroVax. If 5 minute updates are required, as hypothesized in the previous section, we suspect only LINCOM will remain viable. LINCOM now runs on a Microvax II. Combined CPU time when coupled with the sophisticated RIMPUFF puff model was 4 min 40 secs for a slow case. AFWIND's solution method is known to converge quite slowly. Judging from Keiji Hemmi's results on a tiny 10 x 10 x 10 grid version of HOTMAC on an IBM AT at White Sands, we suspect that ENSCO's estimate of greater than 10 minutes of CPU time for a 50 x 80 x 20, 1 hour HOTMAC forecast on a MicroVAX really means much slower than real time. The time needed for just growing the terrain during initialization is considerable, while running RAMS on a MicroVax is really beyond the realm of feasibility.

Though well after the fact, this brings up the choice of computer. It has become clear that economies of scale have propelled 386 desktop computers beyond speeds attained by super-minicomputers just two years ago. That is, the DEC Micro Vax II is more expensive and 5 - 10 times slower than current high-end PCs: IBM PS/2 70, Compac Deskpro 386/25, and a host of cheaper clones. With Weitek 3167 or INMOS T800 accelerators, these desktops run in the range of 1.5 - 4 Megaflops (million floating point instructions per second) and are actually faster than a 30 x more costly DEC VAX 8700. PC graphics, operating systems, multi-tasking, multi-user, and network capacity are also reaching parity with mainframes.

Primitive equation models probably cannot be run usefully on computers less powerful than high end PCs. NPS plans to test RAMS on a current high end PC, while real operational viability awaits systems based on Intel multi-80486 or N10 chips (at 10 - 50 Megaflops, inherently faster than the CPUs used in Cray-like machines). However, we expect that models like RAMS will be limited to pre-planned launch forecasts, rather than emergency nowcasting for at least 5 more years.

A PROJECTED FUTURE VERSION OF LINCOM

At this point we wish to review what we feel Vandenberg really needs in the way of a flow model for emergency nowcasts. An ideal model would have 1) at least 500 m resolution within a few kilometers of release, 2) a domain extending above the boundary layer and more than 50 km from the release point, 3) physics which treats all major forces under stable, neutral, or

unstable conditions, including cloud cover, 4) initial output corrections based on objective analysis, and finally, 5) fairly accurate final results, all in less than 5 CPU minutes.

Save for cloud cover we feel these demands are attainable, but only within the LINCOM class of models. Indeed, we discuss modifications to LINCOM to treat neutral and non-neutral cases over extended domain, improve mass consistency, reduce finite domain and linearity errors, and perhaps even increase speed. That is, a telescoping grid can handle 500 m resolution near release sites and still include a large domain. An above-boundary-layer layer can be added along with an objectively analyzed temperature field which adds buoyancy effects to the wind field. This would allow LINCOM to include the slope flow/seabreeze directly in the physics, instead of through objective analysis corrections, as done currently. Rather than a single mean wind vector taken from one tower at a time, we include all towers in the initial mean wind field. Each wave number will then have its own mean wind vector. Since the solutions remain analytic, this means that perturbations from these more highly specified means will be smaller. This in turn bolsters LINCOM's linearity assumption. As before, the perturbations will be transformed back to physical space and added to the means to give a flow field which includes artificial terrain.

Moreover, we can go further by taking this initial output wind field and gradually damping the flow over the artificial terrain. We then input to LINCOM the new means based upon this revised output and run the model a second time! This revised

output minimizes the effect of artificially finite boundaries. The method also preserves the mass consistency currently lost in combining output fields based on single tower means. It also requires that solutions be procured just twice per flow field, rather than once for every tower input (twenty-seven times in Vandenberg's case). The latter approach should make the method as fast or faster than an equivalent but less accurate look-up table. That is, buoyancy effects would add another dimension to look-up tables, slowing useage and at least tripling memory storage. The frictionless outer layer assumption on which such tables are based also loses validity. The new output's only drawback is that exact matching with tower winds will relax to the level of resolution provided by the highest wave number.

Julian Hunt markets a similar three layer model which is considered current state of the art for LINCOM's model class. However, the new LINCOM would be superior in several ways. That is, Hunt's model relies on slow numerical solutions. Due to the propagating gravity wave problem mentioned above, the model also cannot treat surface based inversions. Artificial terrain effects remain undamped and, since full advantage is not taken of the input data, estimated perturbations about the mean fields will be larger and thus less valid. Finally, without a stretched grid, the Hunt model cannot account for both complex terrain near a plume release site and the extended terrain needed to treat long range plume transport.

CONCLUSIONS

In summary we suspect that

1) AFWIND will not be viable at Vandenberg, due to the slow solution method, convergence problems, limited physics, and lack of objective correction.

2) HOTMAC's size and speed will limit its use to pre-planned launches on computers considerably faster than a Micro Vax II. Its hydrostatic assumption will also limit its accuracy over Vandenberg's steep slopes and complex terrain, particularly with regard to entrainment/plume fumigation episodes, and stratocumulus cloud development

3) SRI COMPLEX has no physics for unstable or neutral cases and is not very useful for these conditions. Under stable conditions, the physics included is limited, but perhaps useable. However, this model also does not use objective correction and thus has the potential to stray from the initial tower/sodar input field, particularly along steep slopes. As we gain experience with SRI COMPLEX we may amplify on some details, but this is not likely to alter our basic conclusions.

4) LINCOM represents a more current class of diagnostic models. Although LINCOM's physics is limited to mechanical effects, comprehensive only for the neutral case, they still apply to both unstable and stable conditions. Its linear basis limits accuracy to modest slopes, but qualitative trends are properly diagnosed and objective corrections mitigate much of the error stemming from simplifying assumptions and the lack of a buoyancy term needed for non-neutral cases. Speaking for all

the models, we caution here that mitigation occurs only within the domain of interpolation by the tower network and does not extend to extrapolation beyond the local regime. For example, Vandenberg's on-line network of 27 towers does not presently include the mesoscale eddy region south of Pt. Arguello, Miguelito Canyon, Lompoc itself, or the high ridge region northeast of Vandenberg which instigates much of the long range upslope flow. We understand that additional towers designed to address some of these data gaps are in the planning stages and also note that the Santa Barbara Air Pollution Control District maintains an on-line network of input from 40 additional towers within a 30 mile radius of Vandenberg.

Be that as it may, we conclude that LINCOM is distinctly better than the other diagnostic models. However, its lack of non-neutral physics and absolute mass consistency argue against its deployment at Vandenberg as the sole nowcasting tool.

5) RAMS resolves many of the limitations encountered with HOTMAC and expresses the current state of the art in prognostic primitive equation models. Its major appeal is its presumably more realistic treatment of clouds, small scale entrainment, and fumigation in complex terrain. But RAMS' boundary layer parameterization needs to be improved. As with HOTMAC, RAMS' robustness limits its speed and usefulness to special studies and perhaps pre-planned launches, at least until available computer power increases by two to three orders of magnitude.

6) Current 386 desktop computers can support nowcasts for sophisticated diagnostic flow/puff model tandems. Within 3 - 5

years the Intel 80486 or N10 chip based computers will allow operational desktop forecasting using prognostic primitive equation models, currently used only for research purposes on Cray class machines. However, nowcasting will remain the purview of diagnostic models for at least 5 years.

7) In view of the fundamental limitations of the other diagnostic models, it seems prudent to fully develop the potential of the LINCOM class of models to extend the scope of the physics to non-neutral cases, improve mass consistency, augment the validity of its approximations, minimize boundary artifacts, and further boost speed as in the fashion described above. While maintaining high resolution near the release site, the domain should also be greatly extended to account for long range plume transport, perhaps in the manner of the existing BZ version of LINCOM. Such a model would be superior to all current diagnostic models foreseeable adaptable to emergency nowcasting. However, even such an improved model will retain problems with terrain intersecting inversions and the treatment of clouds. Suitable accuracy with regard to these issues will remain the purview of RAMS and future models.

8) The projected improved LINCOM and RAMS should provide an optimal tandem for emergency nowcasts and pre-planned launch forecasts, when combined with a good puff or Monte Carlo model.

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